SEDIMENT MANAGEMENT IN HYDROELECTRIC PROJECTS BY OPERATING RESERVOIRS FOR DESILTING

H.P. CHAUDHARY, S.B. TAYADE, S.A. KAMBLE AND NEENA ISAAC
Central Water and Power Research Station, Khadakwasla, Pune, Maharashtra ,India

ABSTRACT

Handling of sediment is a major challenge in the design and operation of hydro electric power plants (HEP) particularly in run-of-the-river projects in Himalayan region. Hydro-abrasive erosion of hydraulic turbines due to suspended sediment particles is an important economic issue as it increases the maintenance cost and reduces turbine efficiency, electricity generation and hence revenue. Currently, desilting structures such as settling basins are provided for minimizing entry of silt into water conductor systems. The desilting chambers are designed with the target of removing sediment particles greater than 0.2 mm in diameter by reducing the flow velocities to the order of 0.2 m/s.

The desilting chambers in run-of-the-river hydropower projects require huge underground structures, which contributes a major fraction of the project cost. Substantial reduction in overall project cost can be achieved if the reservoir itself can be utilized as a settling basin. The sediment thus deposited in the reservoir need to be periodically removed by drawdown flushing to restore the storage capacity of reservoirs and to maintain the area near power intakes clear of sediment deposition. The reservoir operation is to be optimized considering various aspects viz., shutdown duration of power plants for reservoir flushing and refilling, frequency of turbine replacement. The above aspects are highly site specific depending on reservoir geometry, inflow hydrograph of water and sediment, orientation and crest/invert levels of spillway and intake as well as rule curve for reservoir operation. Hydraulic model studies are essential for investigating various alternatives for optimizing the design and operation of these projects.

Typical case studies of two such run-of-the-river projects viz., Devsari HEP, Uttarakhand and Arun III HEP Nepal, for which mathematical and physical models studies were carried at CWPRS to investigate the possibility of reservoir functioning as settling basin and removing sediment deposition by flushing/sluicing are discussed in this paper. The reservoirs are proposed to be operated at Full Reservoir Level (FRL) during lean flow season and at Minimum Draw Down Level (MDDL) during monsoon season. Sluicing and flushing are to be carried out for removing/minimizing sediment to restore reservoir storage capacity.

Keywords: *desilting basin, hydraulic model, run-of-the-river project, hydraulic flushing, intake layout*

1. INTRODUCTION

When a dam is constructed across the river, the flow velocity reduces drastically and most of the sediment transported by the river is deposited in the reservoir thereby reducing the storage capacity (Morries & Fan 1998). In Himalayan region where huge hydro power potential exists the rivers carry a huge quantity of sediment load during the monsoon due to which the reservoir gets silted and can become non-functional within a few years of operation. Moreover, the suspended load entering the water conductor system increases the maintenance and operational cost of power generation due to hydro-abrasive erosion of hydraulic turbines. To tackle this problem of sediment, several new techniques have emerged in recent years especially with reference to the projects in Himalayan region. Designing the projects as run-of-the-river schemes with low level sluice spillways, drawdown flushing of reservoir, providing open channel desilting basins, pressure flow desilting chambers with continuous flushing, uncommon type of weir arrangements in front of the power intakes in case of dam foot power house, diversion tunnels etc. are few of these techniques(CWPRS 2005, Isaac & Eldho 2016, 2017, 2019, Verma et al. 2013]. Drawdown flushing of the sediment in the reservoir helps in restoring the storage in the reservoir and in keeping the area in front of power intake clear of sediment[Isaac & Eldho 2016]. The suspended sediment which enters into the water conductor system is removed by the desilting chambers [Verma et al. 2013]. These are designed to remove the sediment particles greater than 0.2 mm diameter by reducing the flow velocities to the order of 0.2 m/s. The construction and operation of these desilting basins forms a major fraction of the project cost since, these require huge underground structures in run-of-the-river hydropower projects. If the reservoir itself functions as a settling basin, these structures can be avoided and substantial project cost reduction can be achieved. As each project is unique, the standardization of the designs of these elements is not feasible. Hence, hydraulic model studies are essential before finalizing the designs for each project [Morries & Fan 1998].

Two typical case studies of run-of-the-river projects viz., Devsari HEP, Uttarakhand and Arun III HEP Nepal, for which mathematical and physical models studies were carried at CWPRS to investigate the possibility of reservoir functioning as settling basin and removing sediment deposition by flushing/sluicing are discussed in this paper.

2. DEVASARI HEP, UTTARAKHAND

The Satluj Jal Vidyut Nigam Ltd. (SJVNL) has proposed to implement Devsari Hydro Electric Project (252 MW) on river Pinder in Alaknanda basin, Uttarakhand (CWPRS 2013). The Devsari project site (Figure 1) situated on the Pinder River is located about 245 km upstream of Rishikesh. The river Pinder originates from Pindari Glacier at an elevation of about EL.5200m. The elevation in catchment area ranges from about EL 4,600 m to EL 1,267 m at project site. The total catchment area up to diversion site is 1,138 km^2 with permanent snow covered area of 222 km^2. The project complex consists of 35 m high dam, 5 nos. of sluice spillways (8.5 m (W) X 12.5 m (H) with crest at (El.1272m), 18 km long Head Race Tunnel (HRT). The power intake is designed for a discharge of 120.76 m^3/s with invert elevation at El 1277.00 m. The reservoir is to be operated between Full Reservoir Level (FRL) El.1300 m and Minimum Draw down Level (MDDL) El.1295 m.

1D mathematical model and 3D physical models studies have been carried out to investigate the the possibility of reservoir functioning as settling basin.

2.1 1D Mathematical model studies

The one dimensional mathematical model HEC-RAS 4.1 was applied to simulate the flow hydrodynamics and sediment transport/deposition in the reservoir. The reservoir spreads extends to about 4.5 km along main Pindar river and 1 km along river Kailganga which joins the main Pinder river in the reservoir reach at about 2.5 km upstream of dam axis represented in Figure 2. The geometry data for the model was prepared based on survey data of river Pinder from 14 km upstream to 360 m downstream of dam axis and reach of Kailganga from confluence to 5.5 km upstream. The discharge contribution from the tributary Kailganga was not available and hence, based on the approximate catchment areas, discharge distribution in the ratio of 30:70 was adopted for Kailganga and Pinder branches. Steady and unsteady flow simulations were carried out to calibrate and validate the model for hydrodynamic conditions. Ackers and White (Ackers & White 1973) method were used for sediment transport, as it was found to be suitable for uniformly graded sand and gravel (CWPRS 2011)

Simulation runs were then carried out in the sediment transport mode for assessing the extent of sediment deposition in reservoir. In the sediment transport simulations the downstream boundary of the model was restricted to the dam site. The simulation runs were carried out by maintaining the reservoir water level at FRL EL. 1300 m. Simulations were initially carried out for a period of 4 years from June 2006 to May 2010 (daily hydrograph) to observe the sediment deposition pattern in the reservoir and the prevailing velocity profile near the dam and intake. The total sediment load from developed sediment rating curve was also specified at upstream boundary.

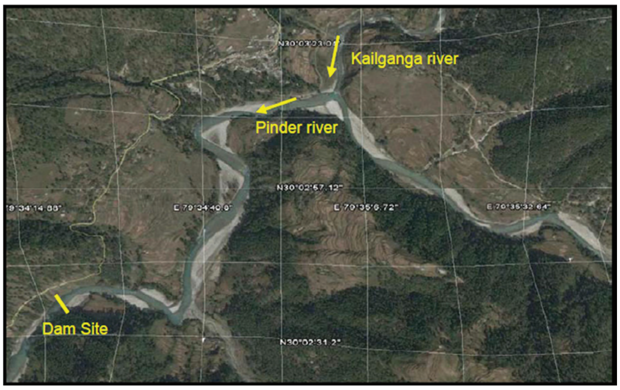

Figure 1 : Location map of the Devsari run-of-the-river hydroelectric project

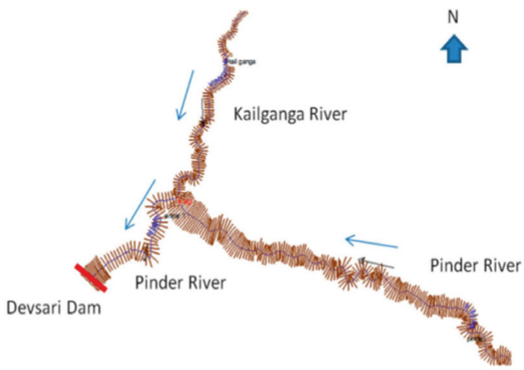

Figure 2 : River system schematic reproduced in the numerical model

Simulation studies were subsequently carried out for obtaining the long term deposition pattern after a period of 30 years (CWPRS 2011). Simulations were carried out for the period from June 1976 to May 2007 by maintaining the downstream water level at dam axis at the FRL EL.1300 m and then at MDDL El.1295 m. The 10 daily average flow series for the above period and total sediment load from developed sediment rating curve were specified as upstream boundaries.

The bed levels at the end of simulation period and velocity profiles are analysed and found that the sediment deposition is in the form of deltaic pattern and starts at the upstream end of reservoir spread on both Kailganga and main Pinder branches (Figure 3 & 4). It can be observed from the velocity profiles that velocity near dam and at intake area during lean flow season is insignificant and of the order of 0.04 m/s. The velocities during the maximum flow can be observed to be of the order of 0.4 to 0.6 m/s.

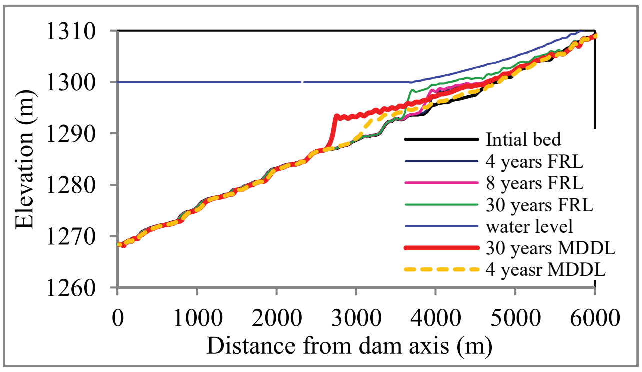

Figure 3 : Longitudinal bed profiles along Pinder River at the end of the simulation period for various reservoir operation conditions

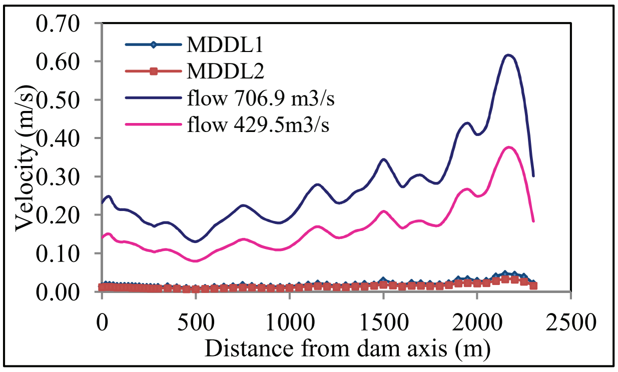

Figure 4 : Longitudinal velocity profiles along Pinder River for various reservoir operation conditions

The prevailing flow velocities for about 1500 m of reservoir were less than 0.2 m/s even for the flood discharge of 429 m^3/s, which is of the order of permissible velocities in desilting basins of hydropower projects. The reservoir itself was functioning as a desilting basin and hence it is not required to provide separate desilting basins similar to typical run-of-the-river hydropower projects.

2.2 3D Hydraulic model studies

The studies were also carried out on a physical scale model to confirm the results of mathematical model and estimating the quantity of sediment entering in the intake. The physical model of Devsari Hydroelectric Project reservoir was constructed to a geometrically similar scale of 1:60 (CWPRS 2013) for the reach of Pinder river from 5.5 km upstream to 0.3 km downstream of dam axis and reach of Kailganga river from 3.5 km upstream to its confluence with Pinder river.

Experiments were conducted for simulating the velocity profiles along the reservoir and estimating the quantity of suspended sediment entering in the intake for discharges of 700, 500 and 300 m^3/s by maintaining reservoir water level at FRL(El 1300 m) and MDDL (El 1295 m). The inflow from Pinder River was 350 m^3/s and Kailganga was 150 m^3/s for 500 m^3/s of discharge. The experiments were carried out for the incoming sediment concentration of 3500 ppm at the upstream end of reservoir. The sediment particles were simulated using walnut shell powder of low specific gravity. The sediment was injected at the upstream end of reservoir in both Pinder and Kailganga rivers. The intake design discharge of 120 m^3/s was drawn through the intake. All the spillway gates were opened equally and partially to pass the surplus discharge. Water samples were collected from the intake at regular intervals. The samples were analyzed for estimating suspended sediment concentration entering the intake.

The flow conditions in the reservoir while maintaining FRL indicated that the velocities in the reservoir were very low and the reservoir functions as a desilting basin. The major part of the incoming sediment was getting deposited at the upstream reach of reservoir spread. Sediment deposition was insignificant downstream of the confluence and practically nil near dam and intake. The deposited sediment can be removed during the proposed annual flushing operations.

The suspended sediment concentrations in the intake was measured for both FRL and MDDL operating conditions for various discharges and the same are given in the Table 1. It was observed that for the incoming sediment concentration of 3500 ppm, the sediment concentration entering the intake varies from 9.70 to 37.9.00 ppm while the reservoir is operated at MDDL. Similarly when the reservoir is operated at FRL, the sediment concentration entering the intake varies from 0.60 to 32.9 ppm.

Table 1 : Suspended sediment concentration passing through the Intake for 3500 ppm

Discharge		**300 m^3/s**	**500 m^3/s**	**700m^3/s**
Reservoir water level (m)	**Sample no.**	**Sediment Concentration (ppm)**	**Sediment Concentration (ppm)**	**Sediment Concentration (ppm)**
MDDL El 1295 m	1	10.0	22.4	32.1
	2	13.0	33.3	33.9
	3	9.70	30.0	37.9
FRL El 1300 m	1	0.60	20.1	31.5
	2	2.60	26.8	27.9
	3	1.20	22.1	32.9

It can be seen from the above table that the sediment concentration entering the intake is significantly lower than the permissible limit for all the discharges and reservoir operating conditions.

3. ARUN HEP, NEPAL

Arun-III hydroelectric project is to be developed as a run-of-the-river scheme, on the river Arun in Sankhuwasabha District, Nepal for generation of 900 MW (Figure 5). The Arun River is one of the major tributary of the Koshi river in the Sapta Koshi basin. The catchment area of the project is 26747 km^2 upstream from the proposed dam site. The project complex consists of a 59 m high concrete gravity dam with 6 nos. of sluice spillways 9 m (W) x 14 m (H) with crest at El. 808 m to pass the flood and sediment during flushing/ slucing. The power intake is designed for a discharge of 344.68 m^3/s with invert elevation at El 819.00 m. The water conductor system consist of a 12.5 km long Head Race Tunnel (HRT). The reservoir capacity / gross storage at FRL is 13.94 Mm^3 and at MDDL is 8.29 Mm^3. The reservoir is to be operated between FRL of El. 845 m and MDDL of El. 835 m. The live storage between MDDL and FRL is 5.65 Mm^3(CWPRS 2014).

1D /2D mathematical model and 3D physical models studies have been carried out to investigate the possibility of reservoir functioning as settling basin.

Figure 5 : Location map of the Arun III run-of-the-river hydroelectric project

3.1 1D mathematical model studies

The 1D mathematical model was developed in HEC-RAS 4.1 for the reach of river Arun from dam axis to about 5 km upstream (end of reservoir spread). The cross sections of the river at intervals of 100 m was used in the model to define the geometry of the reservoir (Figure 6).

Steady and unsteady flow simulations were carried out to calibrate the model for hydrodynamic conditions. Simulation runs were then carried out in the sediment transport mode for assessing the extent of sediment deposition in the reservoir. Various transport equations are available in HEC-RAS for sediment transport computations. Considering the range of sediment size and other parameters governing sediment transport / deposition, the Ackers-White equation was selected for sediment transport computation in the simulation model. The simulation runs were carried out by maintaining the reservoir water level at FRL El. 845 m and MDDL El. 835 m.

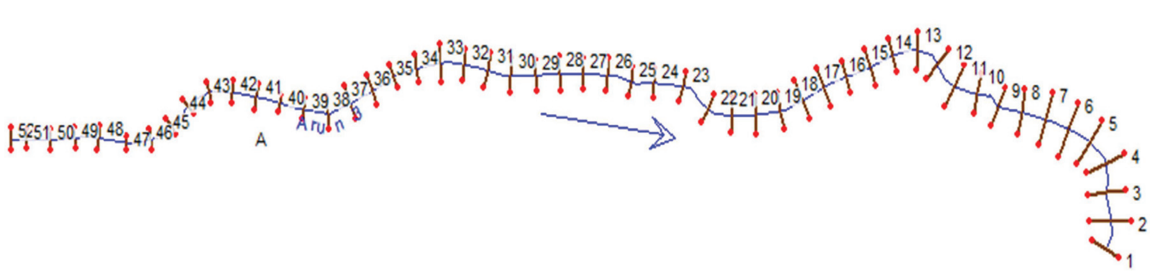

Figure 6 : River system schematic reproduced in the numerical model hydroelectric project

Simulation studies were carried out to observe the long term trend of sediment deposition. Since observed daily flow hydrograph was available for a period of about 38 years from May 1975 to May 2013, simulations were carried out for the same period. Total sediment load from developed sediment rating curve were specified at upstream boundary. Simulations were carried out to estimate the sediment deposition pattern in the reservoir and the prevailing velocity profile near the dam and intake. It was observed from the results that the sediment deposition is in the form of deltaic pattern and starts at the upstream end of reservoir spread in both condition at FRL and MDDL.

It can be observed from the velocity profiles for FRL that velocity near dam and at intake area during lean flow season is insignificant and of the order of 0.01 m/s. The velocity is less than 0.2 m/s for reservoir length of about 3 km, for the average annual flow of 400 m³/s. The velocities during the observed maximum flow of 2198.35 m³/s for 38 years, was seen to be low of the order of 0.35-0.4 m/s along considerable length of the reservoir of about 0.6 km. The velocities observed were of the order of 0.6 m/s for the reach of 1 km upstream of dam axis (Figure 7).

The velocity profiles for reservoir operating at MDDL also indicate the similar trends. The prevailing low velocities indicate that the reservoir functions as a desilting basin during lean flow and hydraulic flushing of reservoir to remove the deposited sediment is required to be carried out during the peak flow.

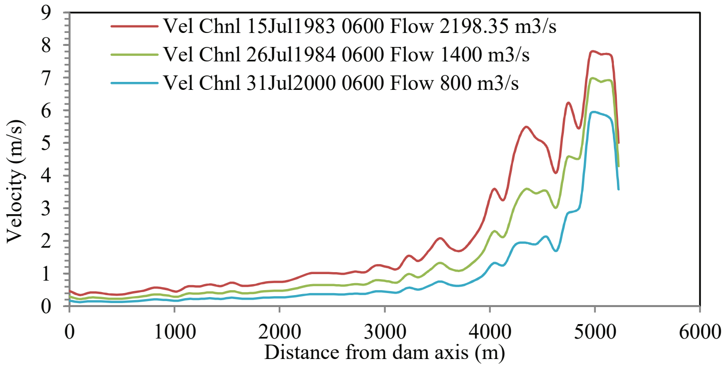

Figure 7 : Longitudinal velocity profiles along Arun River for various reservoir operation conditions.

3.2 3D Hydraulic model studies

The model of Arun-III Hydroelectric project reservoir was constructed to a geometrically similar scale of 1:100 (Figure 8) for the reach of Arun River from 5.0 km upstream to 0.2 km downstream of dam axis (CWPRS 2018).

The studies were conducted for estimating the quantity of suspended sediment entering in the intake. The inflow discharges of 600 m³/s, 800 m³/s, 1000 m³/s and 1500 m³/s were simulated by maintaining the reservoir water level at FRL. The sediment concentration of 2500 ppm and 3500 ppm was simulated in the model using walnut shell powder for suspended sediment. The sediment was injected at the upstream end of model (about 4500 m from the dam axis). The intake design discharge of 344.68 m³/s was drawn through the intake. All the spillway gates were opened equally and partially to pass the excess discharge. Water samples were collected from the intake at regular intervals. The samples were analyzed for estimating suspended sediment concentration entering the intake.

Very low velocities were observed in the reservoir during the simulations. Majority of the suspended sediment was getting deposited in the upstream reach, i.e., from the end of reservoir spread upto 2200 m from the dam axis. Sediment deposition was insignificant further downstream and no sediment deposition was observed near the dam and intake. The flow conditions in the reservoir and sediment deposition on the river bed after 12 hours of simulation for discharges 1500 m³/s, 1000 m³/s, 800 m³/s and 600 m³/s for FRL are presented in Figure 9. Suspended sediment concentration passing through the intake for the above conditions is given in Table 2.

Table 2 : Suspended sediment concentration passing through the Intake for 3500 ppm

Discharge		**600 m³/s**	**800 m³/s**	**1000 m³/s**	**1500m³/s**
Reservoir water level (m)	Sample no.	Sediment Concentration (ppm)	Sediment Concentration (ppm)	Sediment Concentration (ppm)	Sediment Concentration (ppm)
MDDL El 835 m	1	24.5	26.0	42.1	46.00
FRL El 845 m	1	25.6	27.8	28.20	31.50

Figure 8 : View of model reach from dam axis to full reach & **Figure 9** : Simulation of suspended sediment - View of model near dam and Intake. (Q = 1500 m³/s, 3500 ppm, FRL)

The experiments indicated that the reservoir acts as a desilting basin, since most of the suspended sediment of size greater than 0.2 mm gets deposited in the upstream reaches of the reservoir and the sediment concentration entering the intake is insignificant and less than 50 ppm for the inflow concentration of 3500 ppm in the reservoir.

4. CONCLUSIONS

Two typical case studies in which 1D mathematical model and 3D physical scale model simulations were carried out for investigating the concept of reservoir functioning as a settling basin are presented. 1D mathematical model simulations indicated that the flow velocities in the reservoir for sufficient length can be maintained of the order of prevailing flow velocities in desilting basins. The flow velocities exceed the threshold velocity only for shorter periods during annual peak flow. Flushing of the reservoir can be planned during this period to remove the already deposited sediment and restore the storage capacity. Further, 3D physical scales model simulations indicated that most of the suspended sediment settles in the reservoir itself and only a negligible fraction of the incoming sediment enters the water conductor systems except during the peak flow.

It can also be concluded that an integrated approach of numerical model and physical scale model simulations are effective in investigating the sediment deposition pattern and suspended sediment distribution in reservoirs of run-of-the-river hydropower projects.

REFERENCES

Ackers, P. & White, W. R., 1973. Sediment transport: new approach and analysis. Journal of the Hydraulics Division, 99(hy11).

Brunner G. W., 2010. HEC-RAS River Analysis System, Hydraulic reference Manual, Version 4.1, January 2010, CPD-69, U. S. Army Corps of Engineers, Hydrologic Engineering Center(HEC), 609, Second Street, Davis, CA 95616-4687.

CWPRS. 2005. Guidelines for Design of Desilting Basins (Pressure Flow)

CWPRS. 2011. Mathematical Model Studies for Reservoir Sedimentation for Devsari Hydroelectric Project, Uttarakhand, Technical Report No. 4846 of June 2011

CWPRS, 2014 ,Mathematical model studies for Reservoir Sedimentation for Arun III hydroelectric project, NEPAL Technical Report No. :5153 for February 2014

CWPRS. 2013. Hydraulic Model Studies for Reservoir Sedimentation and flushing for Devsari, Hydroelectric Project, Uttarakhand., Technical Report No. 5172 of April 2014

CWPRS. 2016. 2D numerical model studies for reservoir sedimentation of 900MW Arun III HEP, Nepal. Technical Report No. 5424 of September 2016

CWPRS. 2018, Hydraulic model studies for flushing of sediment from reservoir, Arun III hydroelectric project, Nepal. Technical Report No. 5580 of March 2018 Grove, A.T. 1980.

Geomorphic evolution of the Sahara and the Nile. In M.A.J. Williams & H. Faure (eds), The Sahara and the Nile: 21-35. Rotterdam: Balkema. Isaac, N, & Eldho, T.I .2016. Sediment management studies of a run-of-the-river hydroelectric project using numerical and physical model simulations: International Journal of River Basin Management, Vol. 14, No. 2, pp165-175

Isaac, N. & Eldho, T.I., 2017. Sediment management studies of run-of-river hydroelectric power project in the Himalayan region using hydraulic model studies. Sādhanā (2017). doi:10.1007/s12046-017-0666-0.

Isaac N & Eldho T. I. 2019. Sediment removal from run-of-the-river hydropower reservoirs by hydraulic flushing, International Journal of River Basin Management, DOI:10.1080/15715124.2019.1583667 Morris, G&Fan, Jiahua 1998. Reservoir Sedimentation Handbook, McGraw-Hill Book Co., USA

Verma M K. Qamar M Z & Meshram, A. P. 2013. Design Aspects and Model studies for Silt Flushing Tunnels in Hydro Power Projects, International Journal of Emerging Technology and Advanced Engineering (Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal,Volume 3, Issue 12, December 2013))